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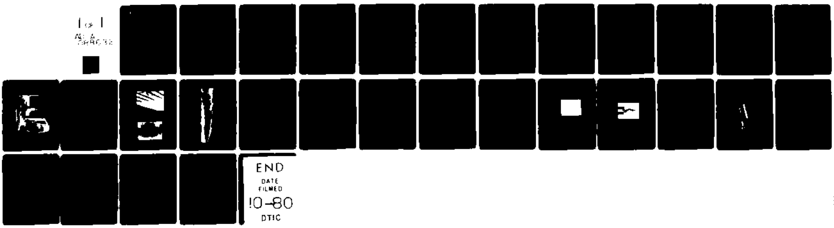

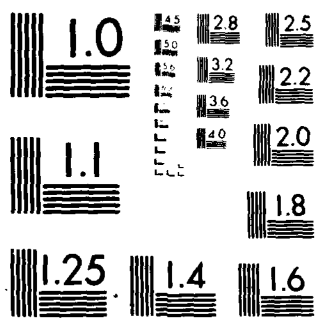

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

DELET-TR-80-11

AD A088632

LONG LIFE X-RAY TUBE FOR AN/TAQ-2 SYSTEM
(MACI Final Report)

Maurice Weiner
ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY

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This report describes a MACI program for obtaining a long life X-ray tube for the AN/TAQ-2 system. New design features, based on a previous research and development program, were incorporated into a commercially available X-ray tube. The new features include a large area, heat treated anode, a getter, and an extended cathode baffle. The program successfully resulted in an eight-fold improvement in tube lifetime.

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LONG LIFE X-RAY TUBE FOR AN/TAQ-2 SYSTEM
(MACI FINAL REPORT)

INTRODUCTION

The AN/TAQ-2 is a portable X-ray system (Fig. 1) used by the Army and Navy for security and medical applications, and is manufactured by Hewlett-Packard Company. A unique feature of this system is that the X-rays are generated by a pulsed cold cathode which contributes to its compact design.

In 1974, as a result of discussions with Electronic Warfare Laboratory personnel, Mr. K. Garoff and Mr. J. Carter of Electronics Technology and Devices Laboratory disclosed an important limitation of the AN/TAQ-2, namely, the short lifetimes of the X-ray tubes; typical lifetimes were about 20,000 pulses. In fact, the tube lifetime was less than the recommended maintenance interval of 50,000 pulses at which point the system was overhauled and the spark gaps cleaned. The tube thus represented a weak link in reliability and maintainability of the AN/TAQ-2. The frequent tube replacements were costly; each tube cost about $200. In order to address the problem of poor tube lifetime, a two-phase program was initiated.

The first phase was a Research and Development (R&D) program aimed at identifying the cause of tube failures and the development of techniques aimed at identifying the cause of tube failures and the development of techniques aimed at eliminating such failures. The R&D phase was conducted both in-house at Electronics Research and Development Command (ERADCOM), and also in a contractual program[1] at ITT Electron Tubes Division ("Long Life X-ray Tubes for Portable Sources," Contract No. DAAB07-75-C-1334, dated June 1975 - August 1976). The second phase was a Military Adaptation of Commercial Items (MACI) Program, which was completed almost entirely on a contractual basis,[2] with the work again performed by the ITT Electron Tube Division ("Long Life X-ray Tube for AN/TAQ-2 System," Contract No. DAAB07-77-C-2657, dated April 1977 - April 1979). In the MACI program a tube available commercially at ITT was modified to incorporate desirable design features from the previous R&D program. The tube was to retrofit into the existing AN/TAQ-2.

The two-phase program ultimately resulted in an X-ray tube with an eight-fold increase in tube lifetime. The results of the overall program are presented in this report.

DESCRIPTION OF TUBE OPERATION

The anode-cathode section of the X-ray tube is shown in Figure 2. The anode is a tapered tungsten rod, with a diameter of 0.250 centimeter (cm), while the cathode consists of several rows of tungsten wires (0.025 millimeter (mm)) symmetrically disposed about the anode.

1 C. Shackelford, Final Report, "Long Life X-ray Tubes For Portable Sources," Contract DAAB07-75-C-1334, ITT Electron Tube Division, Aug 1976

2 C. Shackelford, Final Report, "Long Life X-ray Tubes For AN/TAQ-2 System," Contract DAAB07-77-C-2657, ITT Electron Tube Division, Apr 1979

A 100 kilovolt (kV) pulse, approximately 100 nanoseconds (ns) wide, is supplied to the anode from a Marx circuit. The resultant electron beam is then accelerated to the anode producing X-rays which exit through the aluminum foil window. At 100 kV the X-ray intensity at a distance of 30 cm from the source is 3 milliroentgens per pulse. An option for 150 kV operation exists in the AN/TAQ-2. The intensity at 150 kV is 7 milliroentgens per pulse.

A physical model[3-4] describing the sequence of events leading to the production of X-rays is highly useful since failure mechanisms such as outgassing, anode erosion, and cathode erosion are explainable in terms of the model. The model is described briefly below.

When a high voltage pulse is applied to the anode, current is drawn from the tungsten wires via the field emission effect as described by the Fowler-Nordheim law.[3] The large current densities emitted at the tungsten tip are sufficient to vaporize a small amount of tungsten, creating a plasma ball that serves as a virtual cathode capable of emitting large currents which are then accelerated to the anode. Upon impact of the electrons, the X-rays are produced. The plasma cloud moves toward the anode with a substantial velocity at the rate of 10^4m/s, so one may regard the interelectrode space as decreasing in time. Eventually, as the space between the plasma cathode and the anode diminishes, breakdown occurs and, since the high voltage no longer exists across the interelectrode space, the electrons are no longer accelerated thereby terminating X-ray production.

FAILURE MODES

Cathode Deterioration

Since the cathode is unheated, the initial suspicion was that the source of failure was cathode deterioration. Scanning Electron Microscope (SEM) photographs of the tungsten needles showed that the tapered tips of the tungsten emitters soon eroded (Fig. 3), reducing the field enhancement factor and degree of field emission. However it soon became apparent that even after all the tapered tips of the emitters (which numbered about 120) were eroded, the tube operated normally. Total removal of tapered tips occurred after approximately one thousand pulses. Despite such erosion, the electric field was sufficient to initiate current emission since the diameter is small and there exists significant field enhancement at the edges of the wires. As a result of these findings ITT found it unnecessary to taper the tungsten wires (using an acid dip technique) and the tungsten wires were simply snipped off to the correct length. Cathode erosion became a problem only after the erosion proceeded to the point where the spacing between anode and cathode increased

3 F. M. Charbonnier, "A Brief Review of Vacuum Breakdown Initiation Processes, "Record of IIIrd International Symposium on Discharges and Electrical Insulation in Vacuum," p 15, September 1968

4 G. A. Mesyats, "Explosive Processes at the Cathode of a Gas Discharge," Soviet Tech. Phys. Letters, Volume 1, No. 10, p 385, October 1975

significantly (by as much as a factor of two) so that field emission ceased. Subsequent tests have shown that cathode erosion of this magnitude is not likely to occur until after 300,000 pulses.

Outgassing

Early in the study on tube failure it was found that a tube which failed would often revive after being baked-out and evacuated down to the normal vacuum level (about 10^{-7} torr). These failures were attributed to outgassing in the tube. Once outgassing occurs, a long path discharge may take place. The discharge is of the "long path" type, since the pressure is on the left hand side of the Paschen curve.[5] Depending on the degree of outgassing the long path discharge will occur prior to the formation of the plasma cathode (at higher pressures), or after formation of the plasma cathode and while the plasma cloud is moving toward the anode (at lower pressures). In any event, the X-ray output will be diminished or terminated altogether. A possible solution for this problem, incorporation of a getter, will be discussed later.

Vapor Deposition

During the work on contract DAAB07-75-C-1334, ITT observed that when failure by tube puncture occurred, the glass envelope in the region of the puncture was often coated with deposited tungsten. The metallic deposits set up strong field gradients which increased the likelihood of an arc that punctures the envelope. A simple solution for this type of problem is the addition of a baffle in the anode-cathode region that captures much of the tungsten vapor before it reaches the glass envelope.

Anode Erosion

The most important cause of tube failure appears to be anode erosion. Figure 4, for example, shows an SEM photograph of severe erosion occuring after only 24,000 pulses. An important effect of the erosion is the increase of the anode-cathode spacing. The wider interelectrode space means a reduction of field emission current prior to plasma cathode formation (when the Fowler-Nordheim law applies) and also a reduction in electron beam current after plasma cathode formation (when the Child-Langmuir law applies). In either case the impedance is increased by the wider spacing and, as a result, the voltage delivered by the pulse forming network increases. Thus, the likelihood of an arc will be enhanced.

The tendency toward erosion also increases the metallic deposition on the glass envelope and the cathode. In cases of severe anode erosion tungsten clumps were observed on the cathode that reduced the field enhancement. Anode erosion is thus contributory to other failure mechanisms.

The erosion appeared to start at the grain boundaries and it was postulated that a tungsten anode with larger grain boundaries should suffer less from erosion. Two approaches were tried to increase the boundary size. In the first approach the tungsten was heat treated in an argon atmosphere using an arc welder. The tungsten temperature was raised to 200 degrees

5 S. C. Brown, "Basic Data of Plasma Physics," Technology Press of the Massachusetts Institute of Technology, Cambridge, MA, (1959)

Celsius for approximately one minute. In the second approach a single crystal tungsten anode was used. Both approaches resulted in excellent tube lifetimes. By simply heat treating the anode, with no other design changes, the lifetime improved by at least a factor of 3. The improvement achieved with single crystal tungsten was even better, although the exact comparison is difficult since single crystal tungsten was combined with other features designed to improve life.

The problem of anode erosion can also be attacked by using larger area anodes (Fig. 5). The larger area distributes the erosion over a larger surface, slowing down the rate of erosion per unit area and increasing tube lifetime. In this study two anode sizes were investigated, a standard sized anode with a taper angle of 14 degrees, and a larger diameter anode with an angle of 28 degrees.

EXPERIMENTAL RESULTS

Getters

Early in the program it was found that a tube would fail (no X-ray emission) with no apparent damage to the anode, cathode, or the glass envelope. Such failures were attributed to outgassing. Figure 6 shows the X-ray emission as a function of the number of pulses for a tube initially operated without a getter and then reprocessed with a getter attached to the anode. An additional 30,000 pulses over the original 15,000 were obtained. The increase in lifetime was attributed to the gettering of gasses which evolve during the discharge.

The getter used was a SAES Model No. ST 101, a non-evaporable type. The active material was a combination of zirconium and aluminum. Elements other than hydrogen were adsorbed into the surface of the material. Hydrogen was absorbed into the volume of the getter material. The getter was activated with a radio frequency (RF) coil.

Heat Treated and Single Crystal Large Anodes

Figure 7 shows the lifetimes for both a heat treated and a single crystal anode.[6-7] Both tubes have large area anodes. The longer lifetime of the single crystal anode tube is evident: over 300,000 pulses for the single crystal anode, and about 165,000 pulses for the heat treated anode. The single crystal material was obtained from AREMCO Corporation. Despite the longer lifetime of the single crystal anode, the heat treated anode is more cost effective because of the expense of fabricating the single crystal.

Effects of Anode Size and Gettering Using Heat Treated Anodes

Figure 8 is interesting in that it shows the relative contributions of the large anode and the use of a getter toward increasing lifetime. As indicated in the figure, four types of tube construction are considered: 1) a tube without a getter and with a standard anode; 2) a tube with a getter and a standard anode; 3) a tube without a getter but with a large anode; and 4) a tube with both a getter and a large anode. In all

6 C Shackelford - Op. Cit #1
7 C Shackelford - Op. Cit #2

cases, the anode was heat treated. As expected, the tube with neither getter nor large anode had the least lifetime (about 60,000 pulses) and, conversly, the tube with both features had the greatest lifetime (approximately 140,000 pulses). In addition, the curves show that the large area anode results in a greater improvement in lifetime, compared to the use of a getter. This indicates that anode erosion is more important than outgassing as a cause of tube failure.

Diagnostic Measurements on Large Area Anode

The large area anode is an effective technique for reducing anode erosion per unit area, and thus extending tube life. In theory, because of the larger source size, certain sacrifices are expected: larger focal spot size, decreased resolution, and smaller forward X-ray intensity. In practice, however, virtually no significant differences were detected between the standard size anode and its larger counterpart. The X-ray intensity was in both cases approximately 3 milliroentgens per pulse when measured 30 cm from the source. The X-ray profile for both anode types was measured using thermoluminescent pellets (3.2 mm X 3.2 mm X 0.75 mm) arrayed in a mosaic pattern. A Victoreen reader, Model 2800, was used to measure the dosage received by each pellet. Figure 9 shows that the profiles for both tubes are quite similar with a spot diameter (at 50 percent points) of about 18 cm. In addition, no detectable decrease in resolution was noticed in X-ray photographs of an 0.25 mm wire. Both tubes produced the same degree of X-ray clarity.

Optimization of Pulsewidth

Design changes in the pulser unit are desirable if they extend the lifetime of both the tube and the pulser unit. One possible change involves the voltage pulse supplied by the Marx bank. The pulsewidth should be adjusted so that the pulse terminates just prior to the point in time when breakdown will occur if the pulse persists. In other words, the pulsewidth should be adjusted so that breakdown is avoided while at the same time the maximum possible pulse energy is delivered. If breakdown is allowed to occur, then not only is pulse energy being wasted, but electrode deterioration occurs more rapidly thus shortening tube lifetime. It appears that this situation is prevalent in the present pulser unit. Figure 10 shows the waveform of the tube current. A 50 percent current reversal occurs, indicating that breakdown has occurred in the pulse.

In subsequent measurements the waveforms of the X-ray intensity as well as the current were obtained simultaneously with a Golden Engineering X-ray unit that is similar to the Hewlett-Packard model used in the AN/TAQ-2 (the Hewlett-Packard model was unavailable). Current reversal was also present in the Golden unit. The X-ray pulse was measured with a detector consisting of a fast fluorescent crystal combined with a high speed photomultiplier (EGG model NPM-94). As seen in the waveforms (Fig. 11) the peak X-ray output occurs in the midst of the peak tube current, as anticipated.

Equipment Breakdown

As soon as the lifetime was improved the causes for system failure were no longer connected with the tube itself but were traceable to other parts of the system, which included: pulser circuitry, pressure system, cable connections, and the remote head. In effect, the system rather than the tube, was being life-tested. After the system had accumulated approximately 250,000 pulses, the incidence of system failure, on the average, was every 50,000 pulses. The most common failures occurred in the pulser circuit: faulty pulse forming network (PFN) modules, faulty trigger, and breakdown in the case housing the Marx bank. Two other common sources of system failure were breakdown in the cable connections and in the remote head.

The equipment problems alluded to occurred at 100 kV operation. At 150 kV the equipment problems were exaggerated, creating a situation in which it was virtually impossible to collect meaningful data on tube life. For this reason, very limited data at 150 kV was obtained.

FINAL TUBE DESIGN

The final tube design is shown in Figure 12. It incorporates four new features which have resulted in tube lifetimes in excess of 165,000 pulses. The four features follow: 1) The baffle in the cathode area was extended about 3 cm to decrease metal vapor deposition; 2) A non-evaporable type getter was added to absorb gasses which evolve during the pulse; 3) The anode was heat treated to 2000°Celsius thus increasing the grain boundary size; and 4) A large area anode was incorporated with a taper angle of 28 degrees instead of 14 degrees. The rod connected to the tapered section was made of copper to increase thermal conductivity. A photograph of the tube is shown in Figure 13.

Some thought was given to the use of single crystal tungsten anodes instead of heat treated anodes since the former has a longer lifetime. Ultimately, however, heat treated tungsten anodes were chosen for cost effectiveness ($1000 versus $200). Single crystal tungsten rods are expensive for two reasons. First, it is expensive to grow single crystal material in the size needed for the present application; as far as is known, only one company, AREMCO, supplies single crystal tungsten in the required size. Second, the process of shaping the tungsten into a taper is time consuming, costly, and often unsatisfactory (from the point of view of obtaining good tolerances). At present an ELOX method is used to shape the material. The material cannot be ground since the crystal properties would be destroyed.

IMPLEMENTATION OF MACI GOALS

In order to realize the benefits of the MACI program, such as increased reliability and lower operating costs, the developer of the new X-ray tube, ITT Electron Tube Division, will bid on all procurements of replacement tubes for the AN/TAQ-2 system. ITT has already obtained an EIA number for the tube (No. 9010). Application for a military specification (MIL SPEC) is planned (the present tube in the system does not have a MIL SPEC). A proposed MIL SPEC for the tube has been formulated by ITT

and ERADCOM and appears in Appendix A as well as in the final report[8] of the ITT program.

CONCLUSIONS AND RECOMMENDATIONS

The MACI program has resulted in a long-life tube with an eight-fold increase in pulse lifetime. Use of this tube will result in fewer tube replacements which will reduce operating costs and increase reliability of the AN/TAQ-2 system. Pulser failure (not related to tube failure) occurs on the average of every 50,000 pulses. The lifetime of the new tube thus exceeds the interval of equipment failure by a factor greater than 3. It is recommended that equipment overhauls be performed every 50,000 pulses and the tube be replaced on every third interval. The cost of the new tube is estimated at $200, the same as the 20,000 pulse standard tube. Submission of a MIL SPEC for the MACI tube is planned.

8 C. Shackelford - Op. Cit. #2

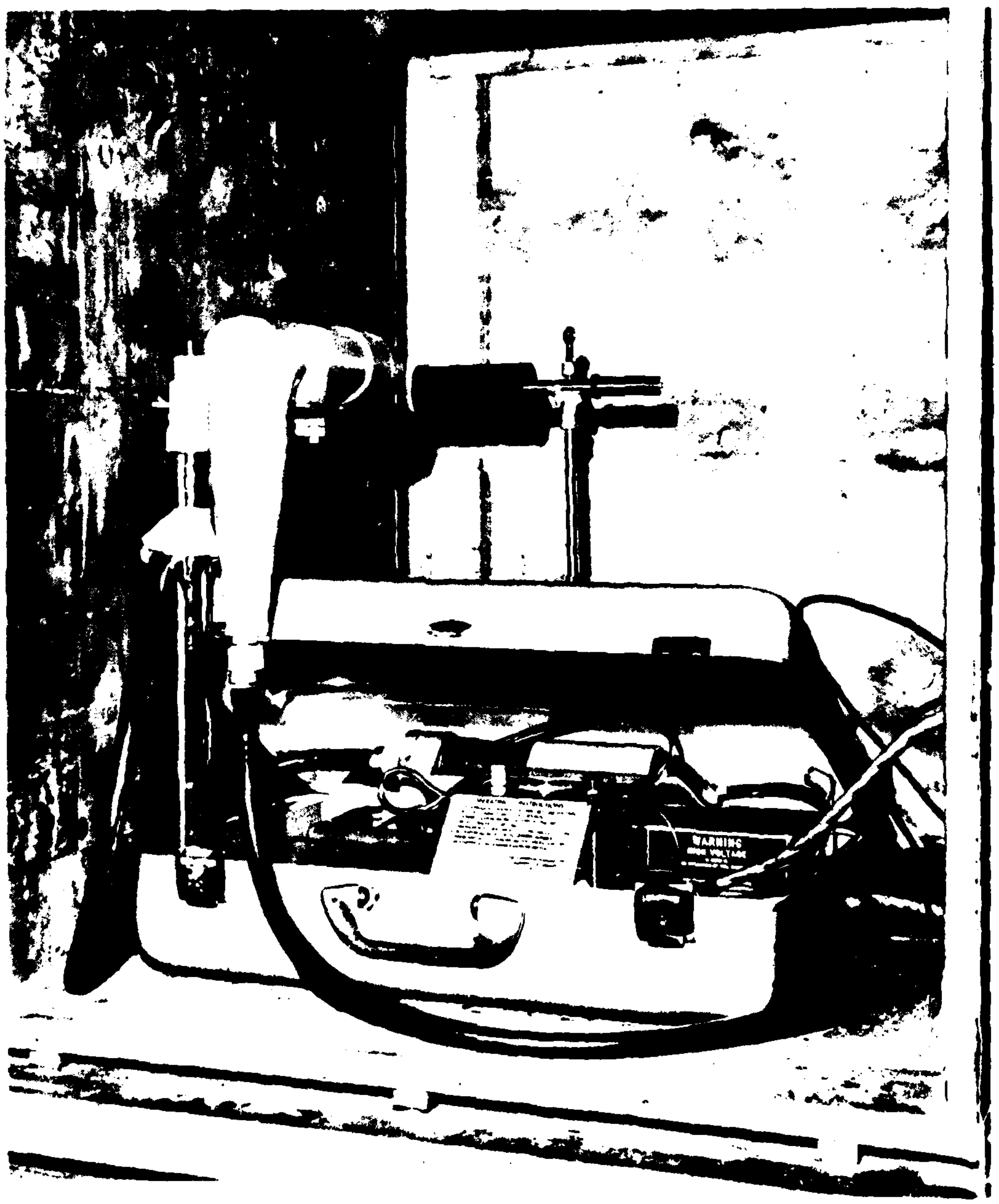


Figure 1. AN/TAQ-2 with Remote Head

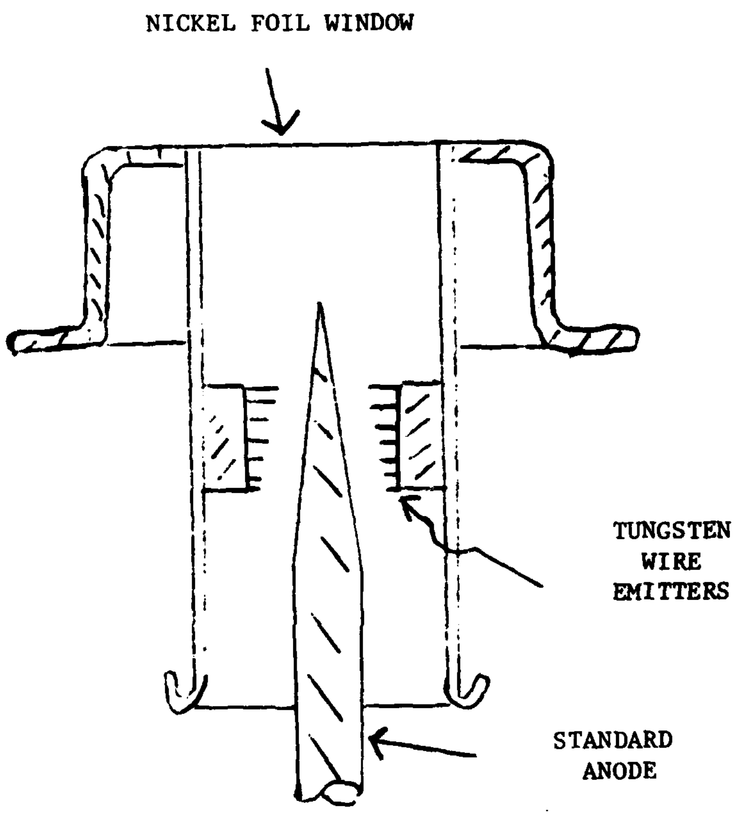


Figure 2. Standard Anode - Cold Cathode Region of X-ray Tube

Figure 3A. Tapered Tungsten Emitters Before Lifetest. Magnification 107X

Figure 3B. Tungsten Emitters After 20,000 Pulses. Magnification 116X

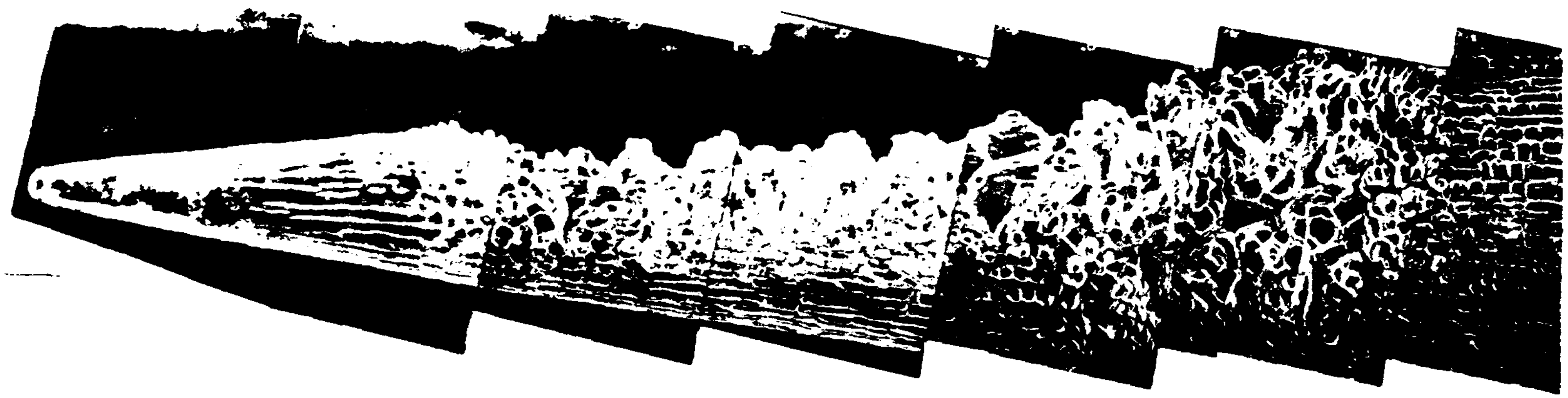


Figure 4. Anode Erosion After 24,000 Pulses, 20 X Mag.

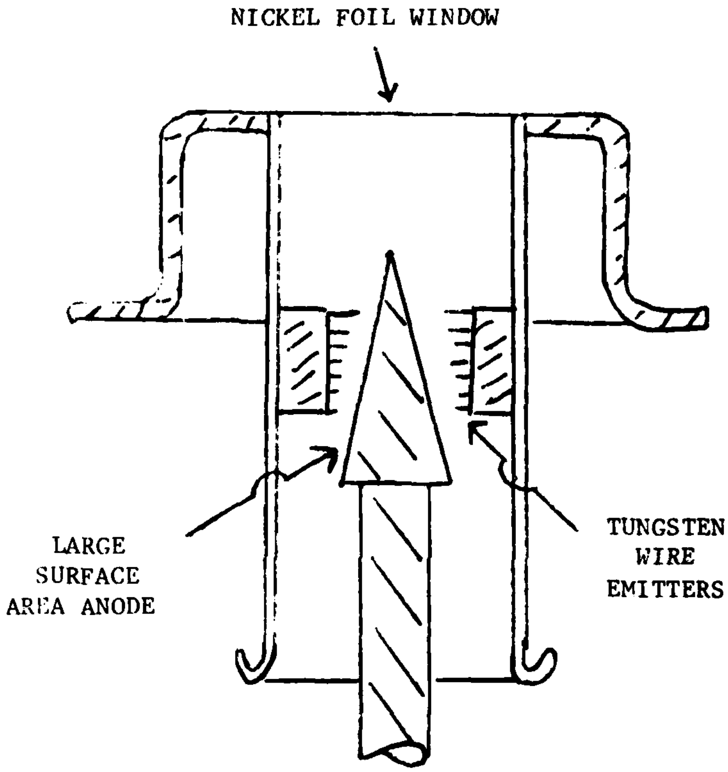


Figure 5. Large Area Anode - Cold Cathode Region of X-ray Tube

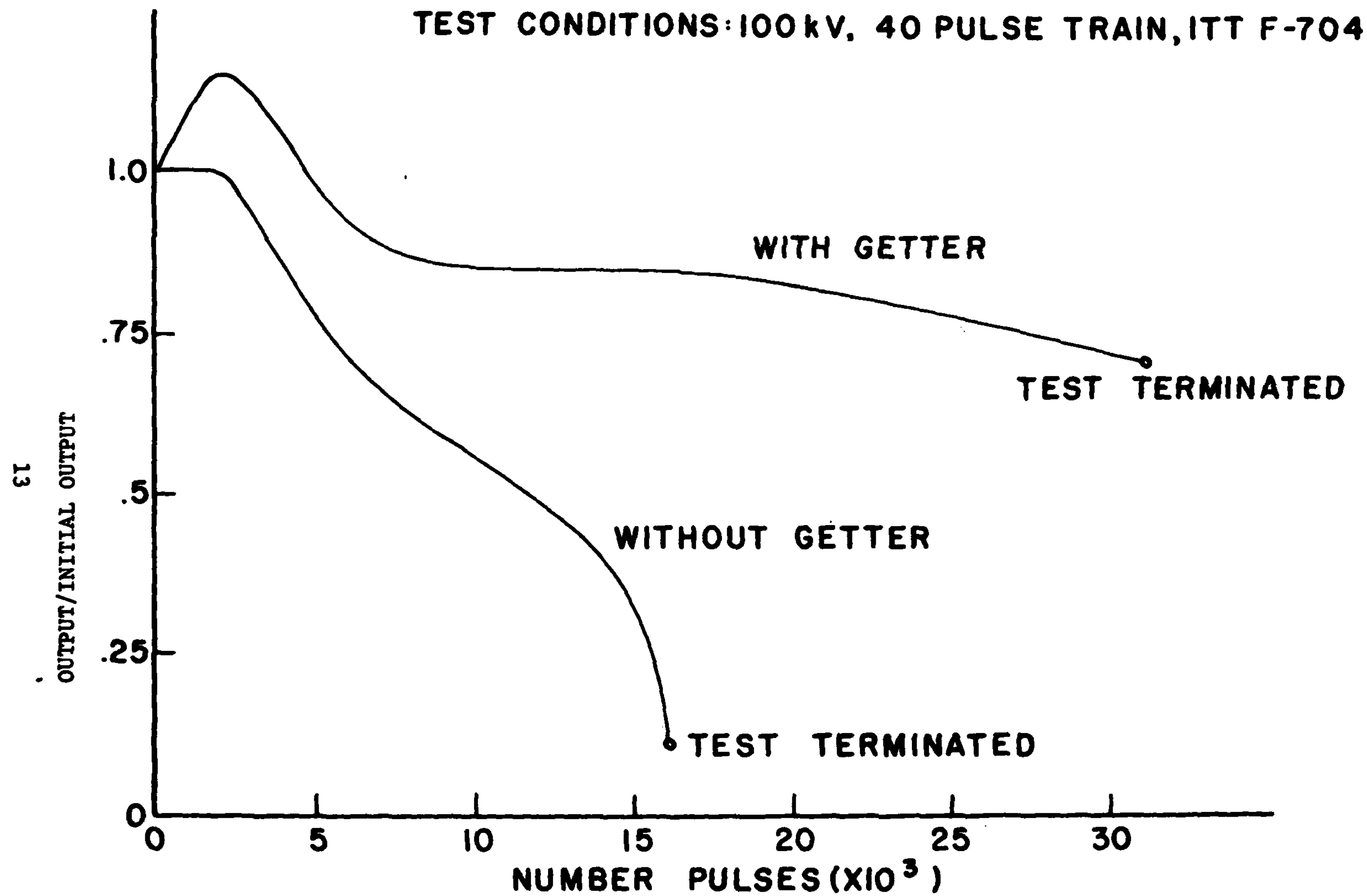


Figure 6. Effect of Getter on X-ray Output

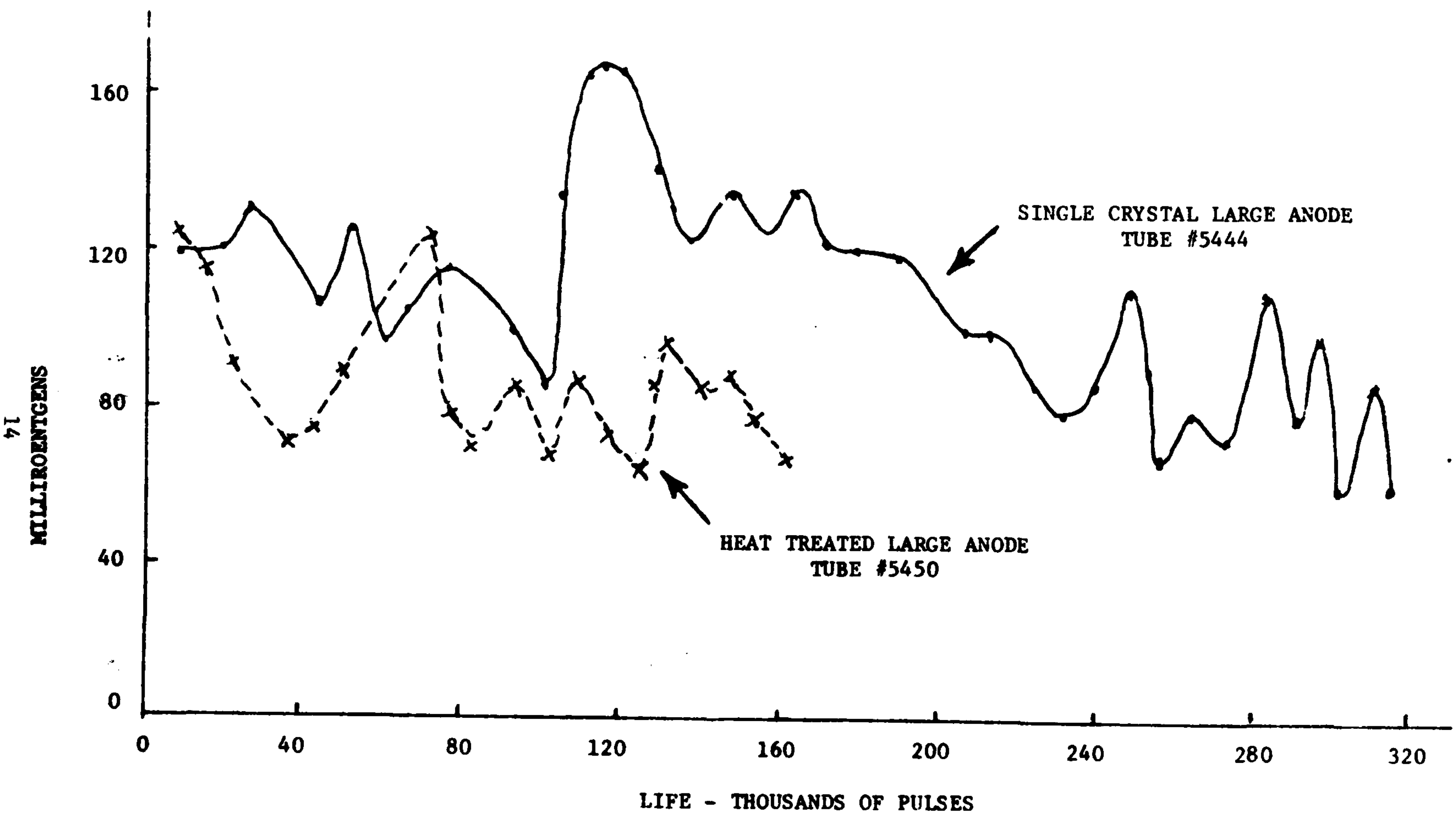


Figure 7. Lifetime of Heat Treated and Single Crystal Tube Anodes

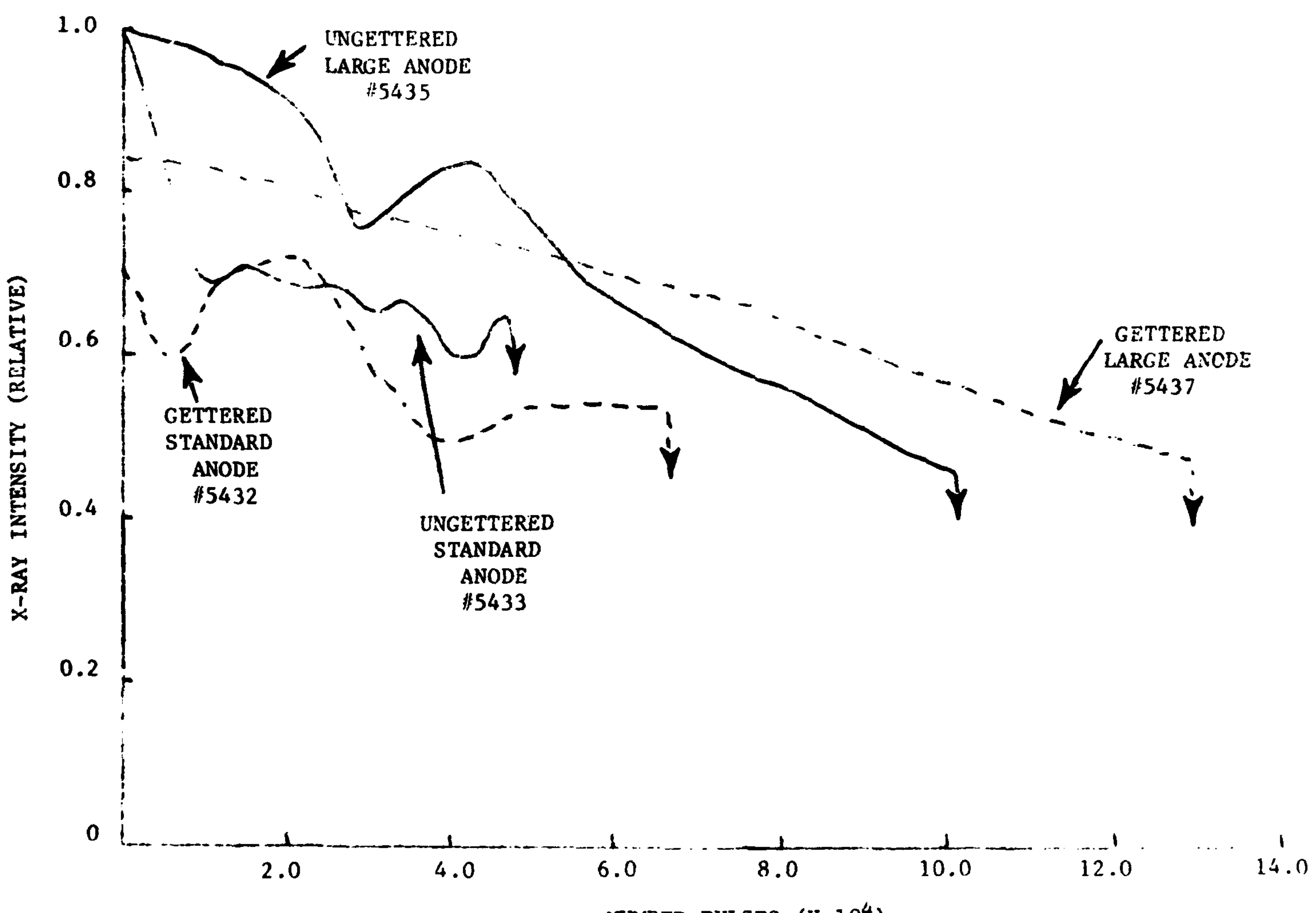


Figure 8. Pulse Lifetime of Tubes with Heat Treated Anodes

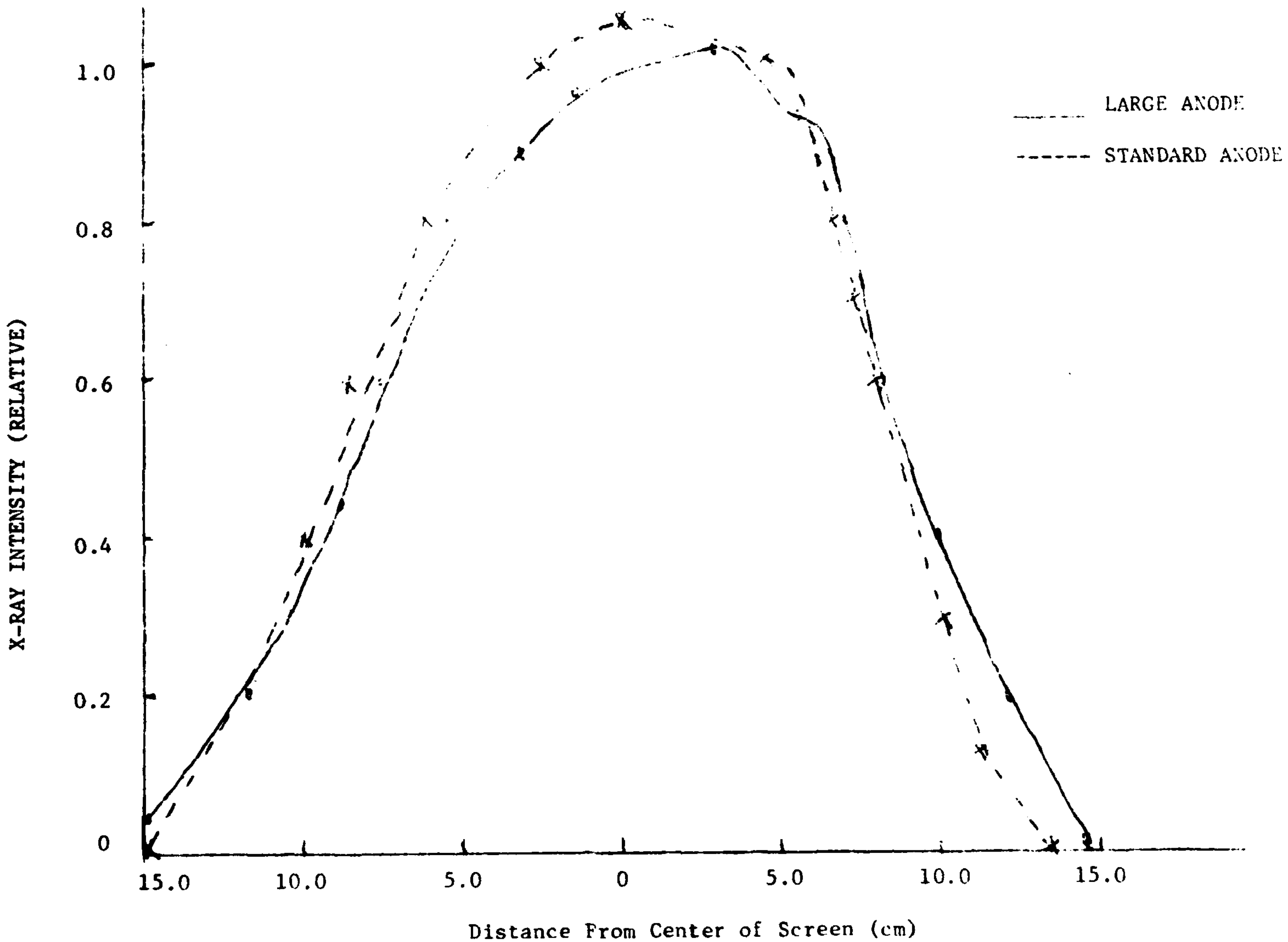


Figure 9. X-ray Intensity Profile on Planar Screen 30cm From Source

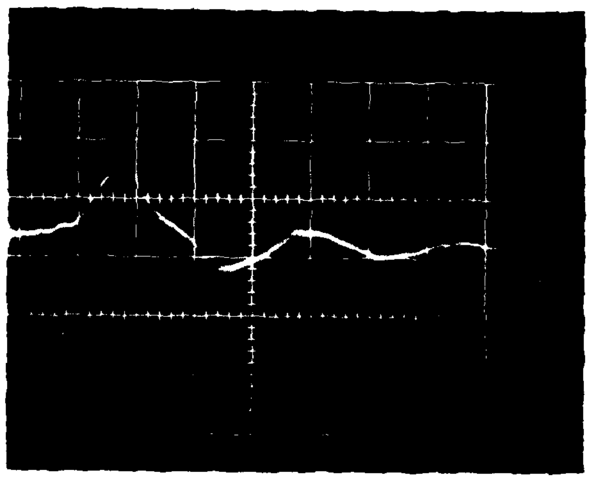


Figure 10. Current Waveform of Tube Current

HP Tube #533C2008

Vertical: 800A/cm
Horizontal: 100 ns/cm

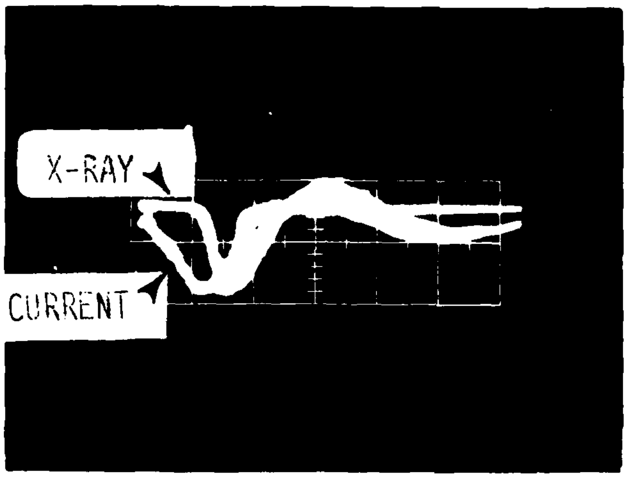


Figure 11. Waveforms of Current and X-ray Pulses

Horizontal: 100 ns/cm
Vertical: Arbitrary

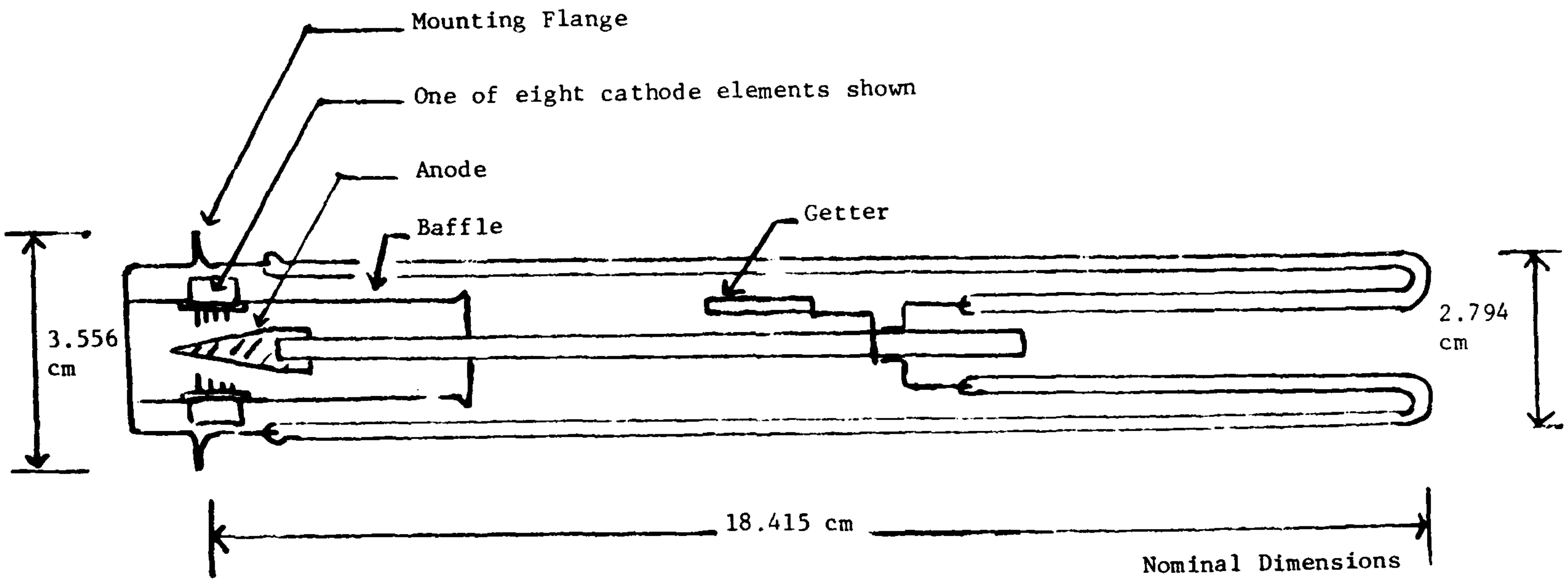


Figure 12. Final Tube Design

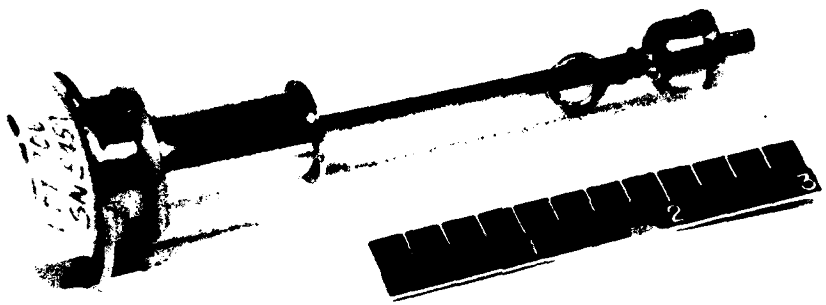


Figure 13. Final MACI Tube

APPENDIX A

Proposed

Military Specification Sheet

Electron Tube, X-ray

Type

The complete requirements for procuring the electron tube described herein shall consist of this document and the latest issues of specification MIL-E-1 and Federal Standard No. 83.

Description: Cold Cathode Pulse X-ray Tube with 0.12 mm nickel filter

Mounting Position: Any

Weight: (99 grams) 3.5 ounces Nominal

Figure A-1

Absolute Ratings:

Parameter:	epy	prr	Dose	Ambient Temperature	Beam Angle	Impedance
Unit:	kV	Hz	mr	$^{\circ}C$	Degree	ohm
Maximum:	150			+75		
Minimum:			Note 1,2,3	-55	35	90
Test Condition:	100	20			Nominal	

General:

Qualification - Required

Table A-1

Requirements for X-ray Tube

Method	Requirement or Test	Notes	Conditions	Symbol	Limits Minimum	Limits Maximum	Unit
	Quality Conformance Inspection, Part 1						
	Output (1)	2,3	100 kV, 30cm 25 pulses	-	65		milliroentgen
	Pulse to Pulse Uniformity	2,3,4	100 kV, 30cm	-	-	-	-
	Quality Conformance Inspection, Part 2						
	Output (2)	2,3	150 kV, 60cm 25 pulses	-	55		milliroentgen
	Beam Uniformity	2,3,5	100 kV, 30cm	-	-	-	
	Quality Conformance Inspection, Part 3						
	Focal Spot Size	2,3,6	100 kV	-	-	4.5	mm
1031	High Frequency Vibration	7,8	No voltage applied	-	-	-	-
	Vibration End Point		Output (1)		65		milliroentgen
	Life	8	100 kV, Group C		150,000		pulse
	Life End Point		Output (1)		50		milliroentgen

Note 1 - The rated minimum dose from the tube in an AN/TAQ-2 or equivalent X-ray system is 65 milliroentgens at 30 cm for 100 kV operation or 55 milliroentgens at 60 cm for 150 kV operation integrated over 25 pulses.

Note 2 - The tube output is measured during operation in an AN/TAQ-2 X-ray system or equivalent circuit. The applied voltage is a square pulse of the specified peak value and of $(60 \pm 5)\ 10^{-9}$ seconds duration. The sum of the rise and fall portions of the pulse is not greater than 20×10^{-9} seconds. The voltage source has a characteristic impedance of 90 ohms. The repetition rate for 100 kV operation is 20 hertz; for 150 kV, 14 hertz. The duty cycle is 2.5×10^{-8}, maximum.

Note 3 - Output measurements are made with a Victoreen 544, or equivalent ion chamber integrating meter located with the chamber centered on the beam and at the specified distance from the X-ray tube window.

Note 4 - Pulse to pulse uniformity is measured by recording 10 groups of 10 pulses each. Five consecutive groups shall not vary from the 10 group average by more than $\pm$ 15 percent.

Note 5 - Predetermine the number of 100 kV pulses necessary to produce approximately 100 milliroentgens at 30 cm. Expose any non-screen industrial X-ray film in a cardboard holder at 30 cm with the film centered on the beam using the determined number of pulses but not less than 20. Develop the film to completion. Using a Macbeth TD-102 or equivalent transmission densitometer, measure the density on the beam axis. Make sets of four orthogonal measurements on each of 15 cm and 10 cm diameter circles centered on the beam. The 15 cm circle measurements shall be not less than 70 percent of the center density. The 10 cm circle measurements shall differ not more than 10 percent from each other.

Note 6 - The focal spot size is measured by the method of Federal Standard No. 83 with the following exceptions:

1. Thirty pulses are used with the distance from the focal spot to the lens at 30 cm.

2. Polaroid film with a fluorescent screen may be substituted for the specified dental film. An optical micrometer may be used to measure the image dimensions.

3. The method of image size calculation is modified to consider a circular or oval image instead of a rectangular one. If A and B are the major and minor axes of the image, the image size is

$$C = \frac{\sqrt{AB}+B}{3}$$

The focal spot size is

$$f = C - 2d \text{ for } f > 2.5 \text{ mm}$$

$$f = \frac{C - 3d}{2} \text{ for } f < 2.5 \text{ mm}$$

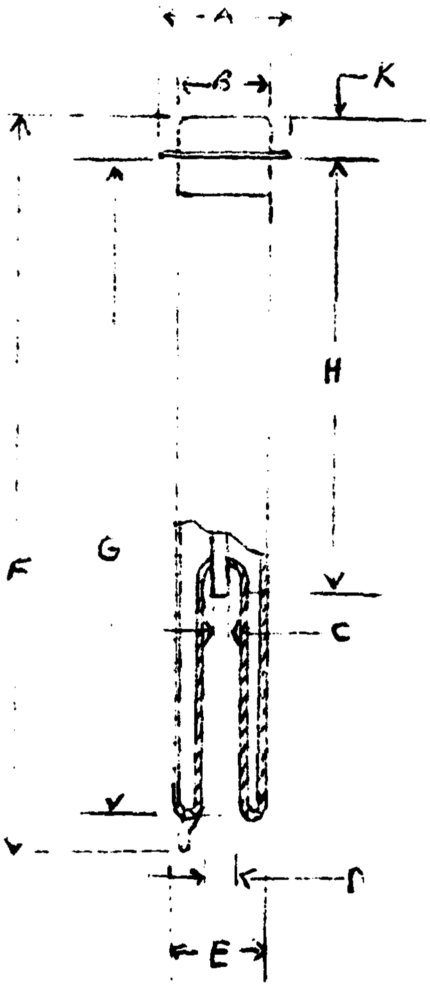
d is the diameter of the pin hole lens.

An image that is distorted into a distinct lunar shape is cause for rejection.

Note 7 - The tube shall be supported solely by its mounting flange.

Note 8 - This test shall be performed during the initial production and once each succeeding 12-calendar month in which there is production. A regular double sampling plan shall be used, with the first sample of three tubes with an acceptance number of zero, and a second sample of three tubes with a combined acceptance number of two. In the event of failure, the test will be made as part of quality conformance inspection part 2, code level D, with an AQL of 6.5. The regular "12-calendar month" double sampling plan shall be reinstated after three consecutive samples have been accepted.

Note 9 - End point readings will be taken at intervals of not more than 10,000 pulses. These readings also constitute part of the accumulated life.



	DIMENSIONS IN mm	
	MINIMUM	MAXIMUM
QUALITY CONFORMANCE INSPECTION, PART 2		
A	35.1	38.5
C	11.4	-
E	-	27.8
G	181.0	186.1
QUALITY CONFORMANCE INSPECTION, PART 3		
B	-	26.2
C	3.2	-
F	-	208.0
H	119.4	122.0
K	-	13.5

Figure A-1 Outline Drawing of Electron Tube Type